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Device and method for measuring the thickness of a transparent sample

The invention relates to a device for measuring the
thickness of a transparent sample, in particular a
glass strip or a glass pane, which preferably has
smooth surfaces, having a first light beam, in
particular a first laser beam, incident on the front
surface of the sample obliquely at a first incident
angle, having a second light beam, in particular a
second laser beam, incident on the front surface of the
sample obliquely at a second incident angle, the first
incident angle and the second incident angle being
different, and having at least one detector for
detecting the light beams of the first and second
incident light beams reflected by the sample, and for
determining their position. The invention also relates
to a corresponding method for thickness measurement
that can preferably be carried out with the aid of the
device in accordance with the present invention.

Glass thicknesses are standardized in the production of
glass panes, glass strips or the like. These standard
thicknesses are provided with tolerances that are to be
observed during production. Substantial quantities of
glass can be saved in mass production if it is possible
to fabricate at the lower tolerance limits by
continuous measurement of the thickness and by a stable
process. Furthermore, the yield of good glass can be
increased if it is possible to enlarge the width of the
marketable glass within the prescribed machine width on
the basis of a good control possibility. Even when
switching between thicknesses at a float glass plant,
it is possible to minimize the times when passing over
from one thickness to the other given a continuous
possibility for measurement, and this likewise
increases the yield of marketable glass.

Devices for contactless automatic measurement of the
thickness of transparent materials in which laser beams
are projected onto the surface to be measured at a
specific angle are known for monitoring the glass or
5   material thickness of transparent materials. The laser
beam is partially reflected at the front side of the
measurement object. A further part of the beam is
refracted into the material, reflected at the rear side
and refracted again at the front side such that the two
10   light beams are retroreflected by the measurement
object. The spacing of the two reflections is a measure
of the thickness of the measurement object and is
correspondingly evaluated.

15   In order to obtain reliable measured values even given
nonparallel surfaces of the measurement object and
despite tilting between the measurement object and
measuring device, DE 41 43 186 A1 proposes a device
having respectively two laser light sources, two beam
20   splitters and two line sensors that are arranged
symmetrically at a deflecting prism in a way such that
the beams from the laser light sources are guided onto
the measurement object in changing directions, and the
reflections at its front and rear sides fall in turn
25   onto the line sensors through the deflecting prism and
the beam splitters. There is the disadvantage here that
the beam path is comparatively complicated and a
multiplicity of optical elements are required. In
addition, it is not possible to detect and to correct a
30   curvature of the material sample, and so the
measurement results are affected by substantial
measurement inaccuracies.

It is therefore an object of the invention to propose a
35   possibility of thickness measurement that can be
implemented easily and can determine thickness very
accurately.

This object is achieved in the case of a device of the type mentioned at the beginning essentially by virtue of the fact that at least one incident light beam substantially parallel to the first or second light
5   beam is directed toward the front surface of the sample, and in that at least one detector is provided for detecting a light beam, reflected by the sample, of the parallel light beam, and for determining its position. By installing a further laser beam parallel
10 to the first or second laser beam incident on the left or right, and by reflecting these parallel beams at the front surface of the sample, for example, a possible radius of curvature of the sample can be determined in the surface section examined. For this purpose, the
15 spacing of these two reflected beams is measured at a known distance from the glass. A correction for the thickness of the sample that is to be measured can then be derived from a knowledge of the radius of curvature. It is possible on the basis of this arrangement with
20 three incident beams to carry out an inclination correction, a wedge angle correction and a curvature correction in a simple way such that the thickness sensor in accordance with the inventive device supplies a high precision for the thickness determined, doing so
25 in conjunction with a comparatively simple and compact design.

Since the third light beam, incident in parallel, is required only for the curvature correction, it can be
30 provided according to the invention that the third light beam is formed such that it can be switched off in order to avoid when making measurements disturbing influences for which the third light beam is not required. This applies, in particular, to the
35 inclination correction and the wedge angle correction.

In accordance with a preferred embodiment of the present invention, the incident light beams and/or the

reflected light beams lie in a common beam plane. Interpretation of the measurement results, and the implementation of the design are then particularly easy.

According to the invention the device and the transparent sample can be moved relative to one another in order, in particular, also to be capable of use in glass production during monitoring of the ongoing production of glass strips and glass panes. This enables a continuous monitoring of the production process. To this end, the device is provided with assigned guide means with the aid of which the sample, for example the glass pane or the glass strip, can be guided past the device. The guide means also serve for aligning the transparent sample in front of the device for measuring its thickness such that the sample can be arranged in a defined alignment in front of the thickness sensor. This particularly serves the alignment of the surface of the sample relative to the optical system of the device, in particular its measuring head.

Since, as a rule, the optical defects transverse to the drawing direction or direction of movement of the glass are larger than the optical disturbances in the drawing direction, it is particularly advantageous in locating these defects when, given a stationary thickness sensor, the relative direction of movement, in particular the drawing direction or direction of movement of the sample, lies in the common beam plane of the incident light beams and/or of the reflected light beams, advantageously perpendicular to the sample normal. Of course, however, the invention can also be applied when the relative direction of movement is arranged not in the common beam plane, but transverse thereto.

In order to achieve a symmetrical design of the
thickness sensor that is advantageous for interpreting
the measurement results, the first incident angle and
the second incident angle can lie in the beam plane,
defined by the first and second light beams, on
different sides referred to the sample normal in the
region of incidence. If, given a nonhorizontal
arrangement of the thickness sensor in front of the
sample, the sample normal does not lie in the common
beam plane, the projection of the sample normal into
the beam plane serves as reference. In particular, it
is advantageous when the incident angles lying on both
sides of the sample normal are equal in absolute terms.
They are, for example, of the order of magnitude of
45°.

In order to detect the reflected light beams, according
to the invention two detectors can be arranged at a
spacing from one another, preferably perpendicular to
the surface of the sample, their sensor surfaces
preferably being turned toward one another. It is
normally possible with such a sensor arrangement to
detect in a spatially resolved manner in both detectors
all of the incident light beams reflected at the
sample. CCD chips, line cameras or other spatially
resolving detectors come into consideration as
detectors.

It is recommended according to the invention that the
region of incidence of the incident first, second and
third light beams on the sample is smaller than the
spacing of the two mutually opposite detectors, which
preferably detect all the reflected light beams. The
region of incidence defined by the points of
impingement of all the incident light beams on the
front surface of the sample is advantageously selected
such that all the reflected light beams are detected in
the detectors.

In order to minimize the number of light sources, in particular lasers, required, it is possible in accordance with a preferred embodiment to provide two beam splitters in order to produce the three light beams from one light beam. Production of the thickness sensor according to the invention is thereby rendered more cost effective. In addition, the adjustment is more simple overall, since the beams emerging from the beam splitters emerge at a defined angle such that the beam guidance of the system according to the invention is set after adjustment of the original light beam, the beam splitter unit and, if appropriate, two deflecting mirrors that delimit the optical measuring head. Here, the beam splitters can output the output beam at an angle of 90° to the transiting beam. Incident angles of 45° can be produced easily thereby with the aid of two parallel deflecting mirrors that are arranged perpendicular to the imaginary surface normal of the sample. One of the beam splitters for producing the third light beam can be of switchable design here in order to switch the third laser beam on and off.

In order to evaluate the measurement results appropriately, an evaluation device connected to the at least one detector can be provided for determining the thickness of the sample, an inclination correction, an angle correction and/or a curvature correction being carried out, in particular. The subsequently described, inventive method, in particular, is then implemented in this evaluation unit, although it can also be applied without being associated with the previously described device.

In the inventive method for measuring the thickness of a transparent sample, in particular one with smooth surfaces, it is provided that a first light beam is incident obliquely on the front surface of the sample

at a first incident angle, and the positions of the
light beam reflected at the front surface and of the
light beam reflected at the rear surface are
determined, and that a second light beam is incident
obliquely on the front surface of the sample at a
second incident angle, different from the first
incident angle, and the positions of the light beam
reflected at the front surface and of the light beam
reflected at the rear surface are determined, the
thickness of the transparent sample being determined
from the spacing of the light beams, reflected at the
front surface and the rear surface, of the first light
beam and/or of the second light beam, and an
inclination and/or wedge angle correction being carried
out by comparing the positions of at least a portion of
the reflected light beams.

In order, in addition, also further to detect a
possible curvature of the sample, it is provided that
at least a third light beam is incident obliquely on
the front surface at a known spacing substantially,
that is to say within a possible adjustment accuracy,
parallel to the first or second light beam, and a
curvature correction is carried out by determining the
positions of the light beams, respectively reflected at
the front surface and at the rear surface, of these
parallel light beams.

The first light beam and the second light beam
preferably incident from different sides on the front
surface of the sample in the beam plane, defined by
them, referred to the sample normal in the region of
incidence. In this case the region of incidence is the
region in which the incident light beams impinge on the
sample. Although, in an advantageous configuration,
these lie close to one another in order to keep the
overall size of the measuring head as small as
possible, they strike the surface at least in a

slightly offset fashion in order to avoid a mixing of
the different beam paths, something which would require
a higher outlay on the measurement and evaluation
electronics. During application of the method, the
5   sample and thickness sensor are preferably aligned such
that the sample normal lies in the common beam plane of
the first and second and, if appropriate, also the
third incident and reflected beams.

10   In order to achieve a high degree of symmetry in the
system, something which facilitates the interpretation
of the measurement results, the first and the second
incident angles can be equal in absolute value, and are
preferably approximately 45°.

15

According to the invention, the spacing from the sample
is determined in each case when impinging on the
detector from the position of the light beams
preferably reflected at the front surface for the
20   purpose of the inclination and/or wedge angle
correction, a wedge angle and/or an inclination
correction being undertaken when spacings do not
correspond. When comparing the spacings from the
samples, it is possible to consider a different beam
25   path, for example through incident angles of different
absolute value.

According to the invention, from a non-corresponding
spacing of the reflected light beams of the first and
30   of the second light beam it is then possible to
determine a wedge or inclination angle with the aid of
which a correction of the previously determined
thickness value is undertaken.

35   According to the invention, in order to determine a
curvature the spacing between the reflected light beams
of the third light beam and the first or second light
beam, substantially parallel thereto, can be

determined, and a curvature correction can be carried out. It is advantageous to this end that the radius of curvature and/or angle of curvature are/is determined from the spacing between the reflected light beams of the third light beam and the first or second light beam substantially parallel thereto. The previously determined thickness value already corrected by the inclination or wedge angle correction is then thereby further corrected.

Furthermore, it is possible according to the invention to use the relationship $D=2/R$ to determine the refractive power D from the radius of curvature R.

Further advantages, features and possible applications of the present invention also emerge from the following description of an exemplary embodiment and from the drawing. In this case, all the features described and/or graphically illustrated are part of the present invention, irrespective of their combination in the claims or of their back references.

In the drawings:

figure 1   shows a schematic plan view of an inventive device for measuring the thickness of a transparent sample;

figure 2   shows a schematic overview of the beam path for a thickness determination;

figure 3   shows a schematic overview of the beam path for an inclination correction;

figure 4   shows a schematic overview of the beam path for a wedge angle correction;

figure 5   shows a schematic overview of the beam path
            for a curvature correction; and

figure 6   shows a schematic overview of the beam path
            for a thickness determination given a curved
            sample.

Illustrated schematically in figure 1 is a thickness
sensor 1 that constitutes a device for measuring the
thickness of a transparent sample with preferably
smooth surfaces. The sample is a glass strip 2 or a
glass pane.

The thickness sensor 1 has a laser (not illustrated)
that produces a focused parallel light or laser beam L
that runs through two beam splitters 3, 4 arranged one
behind another. The laser beam L is split up in the
beam splitters 3, 4 into a total of three laser beams
L1, L2, L3. The first laser beam L1 traverses the two
beam splitters 3, 4 in the direction of laser beam L,
strikes a first mirror 5 at an angle of approximately
45° and is reflected there. In the second beam splitter
4, the second laser beam L2 is coupled out of the laser
beam L at an angle of approximately 90°, strikes a
second mirror 6 at an angle of approximately 45° and is
reflected there. The two mirrors 5, 6 delimit the
optical beam space, forming the measuring head, of the
thickness sensor 1 and are arranged parallel to one
another on opposite sides of the beam splitters 3, 4
with reflective surfaces turned toward one another. The
mirrors 5, 6 are arranged here perpendicular to the
surface of the glass strip 2. An arrangement of the
thickness sensor 1 that is substantially mirror-
symmetric with regard to laser beams L1 and L2 is
thereby achieved. However, the invention is not limited
to this advantageous arrangement.

The laser beams L1 and L2 deflected by the mirrors 5, 6
are incident on the front surface 8 of the glass strip
2 through a front opening 7, turned toward the glass
strip 2, of the thickness sensor 1 at incident angles
5   α1 and α2 of 45° in each case, the incident angles α1
and α2 having different signs, referred to a sample
normal 9, in the region of incidence 10 of the beams L1
and L2 such that, given an incident angle α1 or α2 of
equal absolute value, the beams L1 and L2 are incident
10   on the front surface 8 of the glass strip 2 from
different directions, specifically from the left and
right.

There, the incident beams L1 and L2 are partially
15   reflected and are incident as reflected laser beams
L1', L2' on appropriately arranged detectors 11, 12.
Another portion of the incident light beams L1 and L2
is refracted into the glass strip 2, reflected at the
rear surface 13 and emerges from the glass strip 2
20   after renewed refraction at the front surface 8. These
further laser beams L1'' and L2'' reflected at the rear
surface 13 run substantially parallel to the light
beams L1' and L2' reflected at the front surface and
also are incident on the detectors 11, 12.
25

To this end, the detectors 11, 12 are respectively
arranged in a parallel fashion in front of a mirror 5,
6, and have sensor surfaces that are turned toward one
another and are substantially aligned perpendicular to
30   the surface 8 of the glass strip 2. The detectors 11
and 12 are arranged such that they respectively can
collect the two reflected laser beams L1' and L1'' or
L2' and L2'' of the first and second incident laser
beam L1 and L2, respectively, and can determine their
35   position. The detectors 11, 12 have position-resolving
sensors with the aid of which the position of a light
beam incident on them can be accurately determined. CCD

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chips, line cameras or such sensors are suitable for this purpose.

Produced in the beam splitter 3 upstream of the beam
5   splitter 4 is an incident laser beam L3 that is parallel to the second incident laser beam L2 and is, like the laser beam L2, deflected at the mirror 6 and runs parallel to the laser beam L2 at a spacing s within the range of accuracy of assembly. The third
10 laser beam L3 strikes the front surface 8 of the glass strip 2 in the region of incidence 10. Here, the region of incidence 10 is defined by the region in which the incident laser beams L1, L2 and L3 strike the front surface 8. This region of incidence 10 is smaller than
15 the spacing of the two opposite detectors 11, 12, and extends approximately over half their spacing. The arrangement of the laser beams L1, L2, L3 and the detectors 11, 12 is selected such that the reflected beams L2', L2'' and L3' of the second and third
20 incident beams L2 and L3 are incident on the sensor surface of the detector 11, and the reflected beams L1' and L1'' of the first incident beam L1 are incident on the sensor surface of the detector 12.

25 The known position of the detectors 11, 12 in the thickness sensor 1 and relative to the glass strip 2 or an optimum measuring position thereof can be used to determine the accurate positions of the reflected laser beams L1', L1'', L2', L2'' and L3' in absolute terms
30 relative to the front surface 8 of the glass strip 2 and/or relative to one another. In an evaluation device (not illustrated), this information can be used to determine the thickness d of the glass strip 2 and to carry out an inclination, wedge angle and curvature
35 correction.

The three incident light beams L1, L2 and L3 define a common beam plane 14 in which the sample normal 9 also

lies. Consequently, the reflected light beams L1',
L1'', L2', L2'' and L3' also lie in the beam plane 14.
Even if this arrangement is preferred, it is also
possible in the case of an inventive thickness sensor 1
5 for the beam planes of the incident and the reflected
laser beams to fall apart. In this case, the sample
normal also does not lie in one of the beam planes.

The previously described thickness sensor 1 can be
10 used, in particular, in order to measure the thickness
d of the sample 2, in particular a glass strip or a
glass pane, immediately during production. In this
case, the glass strip 2 or the glass pane is then moved
past the thickness sensor, and the thickness d of the
15 sample 2 is measured continuously or at prescribed time
intervals. The direction of movement 15 of the glass
strip 2 then preferably also lies in the common beam
plane 14.

20 The inventive method for determining the thickness d is
explained below. The method is preferably carried out
with the aid of the thickness sensor 1, which is, in
particular, arranged perpendicular to the glass strip
2.
25

In order to determine the thickness d of the glass
strip 2, the thickness d of the glass strip 2 is
firstly calculated from the spacing d' of the laser
beams L1', L1'' reflected from the first laser beam L1
30 at the front and the rear surfaces 8, 13 of the glass
strip 2. Assuming that, given parallel front and rear
surfaces 8, 13, the glass is completely flat, and the
incident angle $\alpha 1$ is accurately known, the thickness d
can be determined with the aid of a simple method that
35 will be explained below with the aid of figure 2.

The laser beam L1 incident from the left at an incident
angle $\alpha 1$ in the illustration in accordance with

figure 2 is partially reflected at the front surface 8
of the glass strip 2 and emerges as reflected laser
beam L1' at the same emergent angle α1. Another part of
the laser beam L1 is refracted into the glass strip 2,
reflected at the rear surface 13 of the glass strip 2
and emerges as reflected beam L1" at the same emergent
angle α1 in a fashion offset parallel to the laser beam
L1' reflected at the front surface 8.

The perpendicular spacing d' between the two reflected
beams L1', L1'' is determined from the position data of
the beams L1' and L1'' on the detector 12 by using the
known incident and emergent angle α (α1 for L1) and the
arrangement of the detector 12 with reference to the
glass strip 2.

The thickness d of the glass strip 2 is then yielded
from the relationship

$$d = d' \cdot \frac{\sqrt{n^2 - \sin^2 \alpha}}{\sin 2\alpha} \, ,$$

d' being the perpendicular spacing between the
reflected beams L1', L1'', n being the refractive
index, and α being equal to the incident angle α1. The
spacing d' is yielded from the measured spacing M of
the beams L1' and L1'' on the detector 12 from the
relationship d' = M · sin α.

In a corresponding way, the thickness of the glass
strip 2 can be determined for the laser beam 12
incident from the right at the incident angle α2. This
results in two first thickness values d1 and d2 that
correspond in the ideal case.

However, in practice the previously mentioned
assumptions of a known unchanging incident angle α and
a flat, parallel sample surface do not obtain.

Furthermore, there are optical disturbances transverse
to the drawing direction or direction of movement 15 of
the glass strip 2. Because the optical disturbances in
the drawing direction 15 are substantially smaller as a
5   rule, the three beams L1, L1' and L1'' are to lie in a
common beam plane 14 with the drawing direction 15 of
the glass strip 2. The influence of this disturbance on
the practical application can be eliminated by this
geometric arrangement.

10

The glass strip 2 can, for example, also be inclined on
a roller track such that the incident angle $\alpha = \alpha 1$, $\alpha 2$
can assume different values. For the correction, use is
made of the second incident laser beam L2, which is
15   incident not from the left, but from the right and lies
in the same beam plane 14. At the same time, a wedge
angle, possibly present, of the glass strip 2 can also
be determined and corrected with the aid of this
system, the method steps being explained below with the
20   aid of figures 3 and 4.

When the incident beam L1 is reflected not at a glass
strip 2 that is aligned perpendicular to the thickness
sensor 1 and in the case of which the sample normal 9
25   coincides with the axis of symmetry of the thickness
sensor, but at a glass strip 2 inclined by an
inclination angle σ, the emergent angle in the beam
plane 14 is not equal to the imaginary incident angle
$\alpha = \alpha 1$, but amounts to $\alpha = \alpha 1 + \sigma$.

30

Use is made for the inclination correction not only of
the beam L1 incident from the left, but also of the
beam L2 incident from the right which, for the sake of
clarity, is not depicted in figure 3. Instead of this,
35   for a comparison a light beam exiting at a horizontal
glass strip 2 at the emergent angle $\alpha 1$ and which
corresponds to the beam L1' from figure 2 is
illustrated without a reference symbol.

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The incident angle α for the second beam L2 is then
α = α2 - σ. The upshot of this is that the beams L1',
L1'' and L2', L2'' reflected from the first and second
5   beams L1 and L2 no longer strike the detector 11, 12 at
the same spacing from the glass strip 2, as would
otherwise be the case because of the symmetric design
of the thickness sensor 1. Thus, a wedge angle
correction must be carried out when the spacing b1 at
10 which the beam L1', reflected at the front surface 8,
strikes the detector 12 is not equal to the spacing b2
at which the beam L2' reflected at the front surface
strikes the detector 11. This is described below:

15 In order to determine the inclination angle σ, the
spacing b1 of the beam L1' reflected at the front
surface 8 from the surface 8 is determined in the
detector 12, the spacing b1 being determined in the
direction of the sample normal 9 of the uninclined
20 sample 2.

Given knowledge of the spacing a of the detector 12
from the point of impingement of the first beam L1 in
the direction of the surface 8 of the glass strip 2,
25 that is to say perpendicular to the sample normal 9, it
holds for the beam L1 incident from the left that:

$$tg(\alpha + 2\sigma) = \frac{\alpha}{b_1} .$$

30 It holds correspondingly for the beam L2 incident from
the right (not illustrated in figure 3) that:

$$tg(\alpha + 2\sigma) = \frac{\alpha}{b_2} .$$

35 The difference b1 - b2 can be determined from the
measured positions or from the beams L1' and L2'

reflected at the front surface 8. It is advantageous to select the difference for the calculation, since a constant amount by which the glass band would have been raised overall stands out. The inclination angle σ can

5   be calculated assuming that $\alpha = \alpha_1 = \alpha_2$. The set incident angle $\alpha = \alpha1 = \alpha2$ for the beam L1 or L2 incident from the left or from the right is enlarged or reduced by precisely this angle, and so the incident angle used in the equation in order to determine the

10   thickness d must be appropriately corrected in order to determine the thickness d of the glass strip 2 correctly.

Furthermore, the glass strip 2 itself can have a wedge

15   angle δ, as illustrated in figure 4. When the spacings M1 and M2 between the laser beams L1', L1'' and L2', L2'' reflected at the front and the rear surfaces 8, 13 are not equal, the glass strip 2 is provided with a wedge. This can be determined from the positions of the

20   reflected beams L1', L1'' and L2', L2'' on the detector.

Given the presence of a wedge angle δ, it is possible in accordance with figure 4 to determine thickness

25   values d1 and d2 respectively for the beams L1 and L2 incident from the left and right, the thickness d of the sample 2 then being yielded from its mean value. It is also possible to average the spacings M1 and M2 between the reflected beams L1' and L1'' or L2' and

30   L2'', and to determine the sample thickness therefrom.

In addition, the glass strip 2 can also further be curved. In order to determine this, the third laser beam L3 is irradiated parallel to one of the first two

35   incident beams, the laser beam L2 in the case illustrated, at a spacing s known from the design of the thickness sensor 1. Here, in the example illustrated in accordance with figure 5 the beam

direction of the beams L2, L3 is reversed by comparison
with figure 1. However, this is not important for the
functional principle. The reflection of the beams L2,
L3 at the front surface can be used to determine the
5   radius of curvature R of the sample 2, as is explained
below with the aid of figure 5.

The beams L2' and L3' reflected at the front surface 8
of the curved sample 2 are incident on the detector 11
10   at a spacing S'. A curvature of the under side of the
glass strip 2 is present when the spacing S' is not
given by the relationship $S' = s / \cos \alpha$ given an
incident angle α of the incident beams L2 and L3. The
positions of the reflected beams L2' and L3' can be
15   used to determine the radius of curvature R, which then
features in accordance with figure 6 in the calculation
of the thickness d of the sample 2.

The measured values are determined in each case for the
20   two incident beams L1 and L2. These then yield two
thickness values d1 and d2 from which the mean value is
formed. In particular, the incident angles $\alpha 1$ and $\alpha 2$,
and therefore also the angles $\beta 1$ and $\beta 2$ are different
for the two incident beams. They are yielded in the
25   case of the inclination correction for the glass strip
2.

Finally, one further correction can be taken into
account, one which is required when the beams L2 and L3
30   incident in a parallel fashion are still not quite
parallel.

The glass or material thickness of a transparent sample
can be determined with a high accuracy of 0.1% upon
35   applying the above-described method, in which an
inclination correction, a wedge angle correction and a
curvature correction are applied one after another. The
inventive device is preferably used for this purpose.

List of reference symbols:

1	Thickness sensor
2	Sample, glass strip
3, 4	Beam splitter
5, 6	Mirror
7	Opening
8	Front surface
9	Sample normal
10	Region of incidence
11, 12	Detector
13	Rear surface
14	Beam plane
15	Direction of movement
L	Light beam, laser beam
L1, L2, L3	Incident laser beams
L1', L2', L3'	Laser beams reflected at the front surface
L1'', L2''	Laser beams reflected at the rear surface
a, A	Spacing of the point of incidence of a light beam on the glass strip up to the detector parallel to the glass strip
b, B	Spacing of the position of a laser beam on the detector from the glass strip perpendicular to the glass strip
d	Thickness of the glass strip
d'	Perpendicular spacing between laser beams reflected at the front and the rear surfaces
s	Spacing of laser beams incident in parallel
M, S'	Spacing of reflected laser beams on the detector
R	Radius of curvature
α	Incident angle
σ	Inclination angle
δ	Wedge angle